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Title: Characteristics of Fissile Solution Systems

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Characteristics of Fissile Solution Systems

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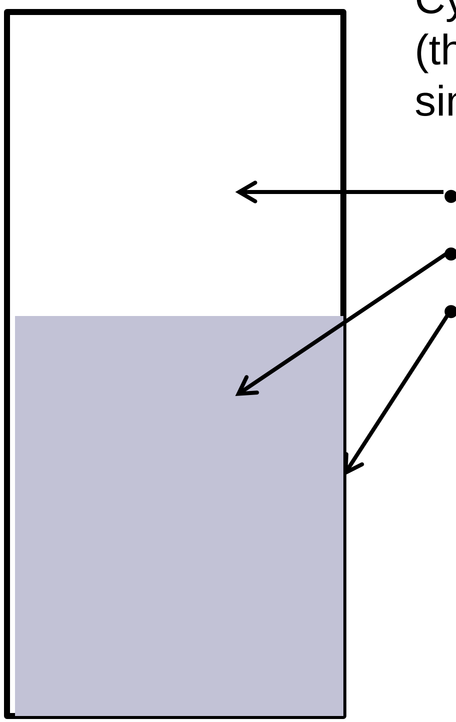
Topics

- **Preliminary Discussion (Modeling Techniques)**
- **Geometric Considerations**
  - Vessel configuration
  - Solution height
  - Height-to-diameter ratio
  - Radiolytic gas holdup
- **Effects of Solution Chemistry**
  - Concentration of fissile material
  - Water content
- **Negative Reactivity Feedback Mechanisms**
  - Temperature of fuel
  - Radiolytic gas generated void
- **Dynamics**
  - Startup and transition to steady-state; power oscillations
  - Stability and reactivity insertions
- **Auxiliary Systems**
  - Gas handling
  - Fuel cooling
- **Summary**

System Modeling

- **MCNP, Partisn used for variety of static data**
- **Integrated System Modeling**
  - Set of coupled nonlinear differential equations that may be solved in time to simulate the dynamics of the overall system.
  - Used for Experiment Planning and Authorization Basis for fast metal critical assemblies including Godiva High Energy Burst Machine at LANL TA-18 and Criticality Experiments Facility (CEF) at NTS/DAF for nearly 20 years.
  - System Model for SHEBA AHR was used for this purpose until decommissioning in 2004

Stylized Fissile Solution System



Cylindrical “bucket” partially filled with fissile solution (throughout presentation the term “bucket” refers to this simple configuration)

- Void above solution
- Fissile solution
- Container

The distinguishing characteristics of fissile solution systems are generally driven by the ability of the fuel to flow, change in volume and redistribute under a variety of forces.

Reactivity & Geometry – Solution Height

Consider the following cylindrical "bucket"

- Height to diameter ratio of 1:1 (choose 50 cm)
- UO_2SO_4 LEU fuel
- Stainless steel container 0.5 cm thick

k_{eff}	Height (cm)	Volume (L)	Δ Height	Δ Volume
1.00	50.00	98.17		
0.99	46.00	90.32	(4.00)	(7.85)
0.98	43.59	85.59	(6.41)	(12.58)
0.97	40.99	80.49	(9.01)	(17.68)
0.96	39.28	77.13	(10.72)	(21.04)
0.95	**37.40**	**73.43**	**(12.60)**	**(24.74)**

← *k_{eff} = 0.95 occurs at approximately 75% of critical height or volume*

Solution height can be controlled to ±0.1 cm; hence, even at keff=0.99 the physical margin from critical is considerable and easily managed

Reactivity & Geometry – Height/Diameter Ratio

H.C. Paxton & N. L. Pruvost "Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U, 1986 Revision", LANL Report LA-10860-MS (July 1967)

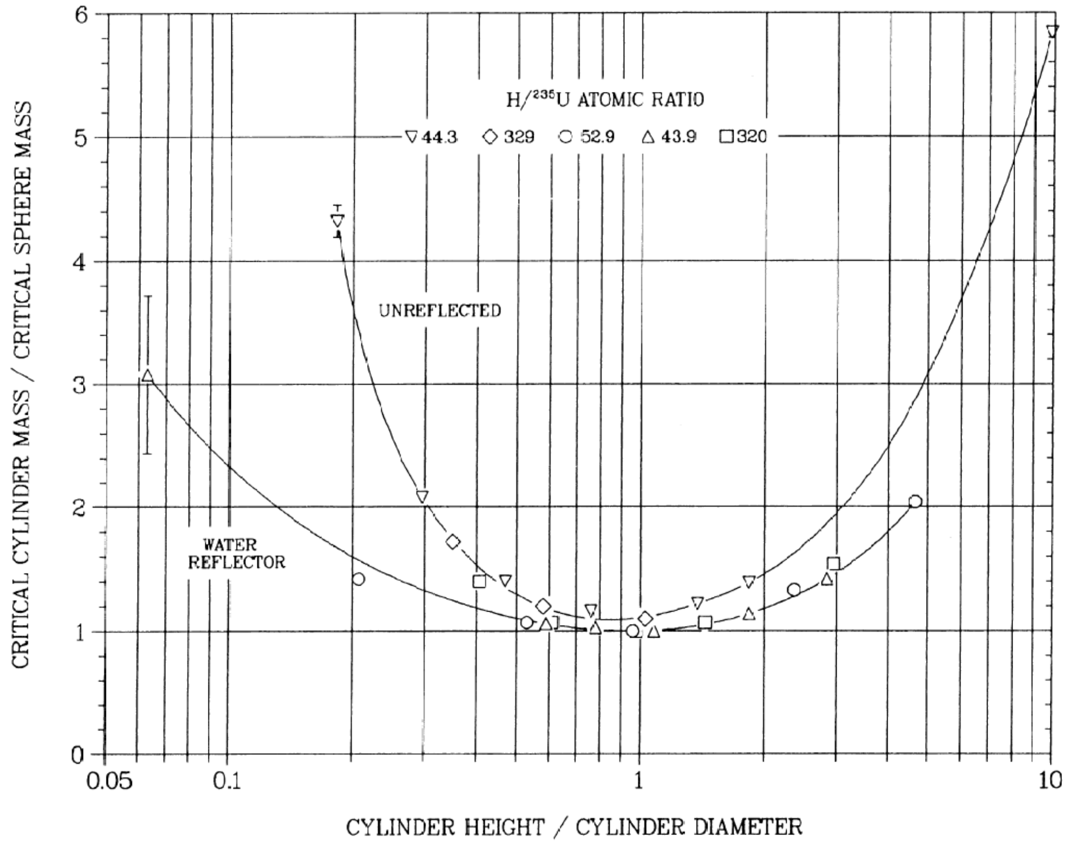
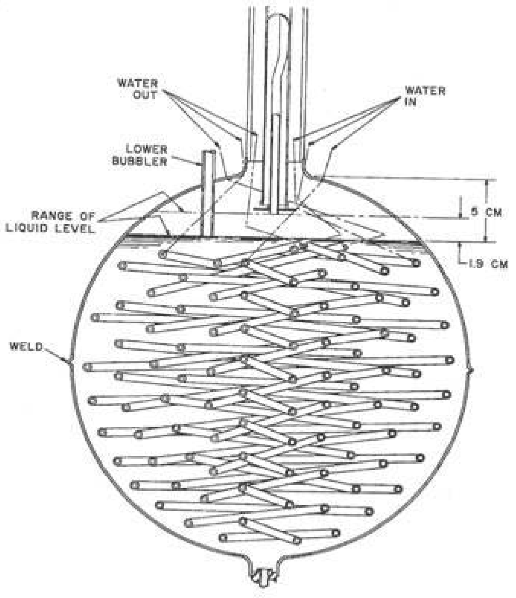


Fig. 4. The ratio of cylindrical to spherical critical masses of $U(93)O_2F_2$ solutions, unreflected and with water reflector, as a function of cylinder height to cylinder diameter ratio.

Critical volume & height increases as H/D moves away from 1.00 in either direction

Power & Geometry – Radiolytic Gas Holdup

SUPO[1] with Cooling Coils



System Model Results

Baseline SUPO; $1.90

- 24.90 kW
- 64.18 ºC
- 2.09% Void

SUPO Without Impeding Coils (same coil dimensions and length but vertically strung)

- 27.97 kW
- 69.16 ºC
- 1.44% Void

Configurations impede transport of gas from core are less efficient

[1]SUPO operated at Los Alamos from 1954 to 1971

Reactivity & Solution Chemistry

Uranium Concentration (19.75% Enriched)

gU/liter	keff	$/gU/liter
134.47	1.01187	0.3005
129.47	0.99992	
124.47	0.98720	-0.3246

Sensitivity to Uranium concentration ~±$0.30/g

Effect of H-O recombiner and/or water makeup system malfunction (100 kW operation assumed)

Time	Start	1 hour	2 hours	3 hours
keff	0.99992	1.00159	1.00792	1.01787
Liters H_2O Loss		2.12	4.24	6.36
$/min		0.0035	0.0083	0.0123

Effect is exponential increase with time

Reactivity & Temperature

MCNP estimates of "bucket" model

Effect	Fuel Temp	Density	Volume (L)	Height (cm)	k_{eff}
Density	90ºC	9.8910E-02	101.159	51.52	0.98656
Cross sections	20ºC	1.0230E-01	98.175	50.00	0.99977

Reactivity feedback factor due to fuel density

$$ALF_{density} = \frac{k_{eff90C} - k_{eff20C}}{k_{eff90C} * k_{eff20C} * \beta * \Delta T} = -0.0241$$

Where β=0.00794 is the delayed neutron fraction, 70 is ΔT

Result is -$0.0241 negative reactivity feedback per degree C

Spectrum effects determined by replacing ".50c" cross sections with ".12c" cross sections and lwtr.01c S(α,β) with lwtr.02c (representing a temperature change of 100K).

Reactivity feedback factor due to cross section

$$ALF_{Spectrum} = \frac{k_{effspectrum} - k_{eff20C}}{k_{eff20C} * k_{effspectrum} * \beta * \Delta T} = -0.0237$$

Result is -$0.0237 negative reactivity feedback per degree C

Combined is an estimated -$0.0478 negative reactivity feedback due to temperature

Reactivity & Void

Fission fragments in solutions decompose water into hydrogen and oxygen generating approximately 0.44 liters of gas per kilowatt per minute[2]. This "radiolytic" gas creates void in the solution fuel effectively reducing its density resulting in a negative reactivity feedback mechanism. Typical void by percent fuel volume is 1 – 3%.

MCNP estimate of "bucket" model at 20ºC with 3% void is 0.99154. This is used in the equation below to compute the reactivity feedback (*PHI_{20}*) at 20ºC

Reactivity feedback factor due to gas void

$$PHI_{20} = \frac{k_{eff20C+3\%} - k_{eff20C}}{k_{eff20C+3\%} * k_{eff20C} * \beta * 0.03} = -35.47$$

Result is -$35.47 negative reactivity feedback per percent of void

[2]LA-2854, STATUS REPORT ON THE WATER BOILER REACTOR. Merle E. Bunker, February 1963

Combined Effect of Temperature & Void

Reactor Model	Temperature ($/ºC)	Void ($/fraction)
“Bucket”	-0.0478	-35.47
SUPO	-0.0344	-34.23
KEWB “A-2”	-0.0318	-44.57
KEWB “B-5”	-0.0554	-48.30
Silene	-0.0547	-72.83

- SUPO operated at Los Alamos
- KEWB reactors operated at North American
- Silene operated at Valduc, France

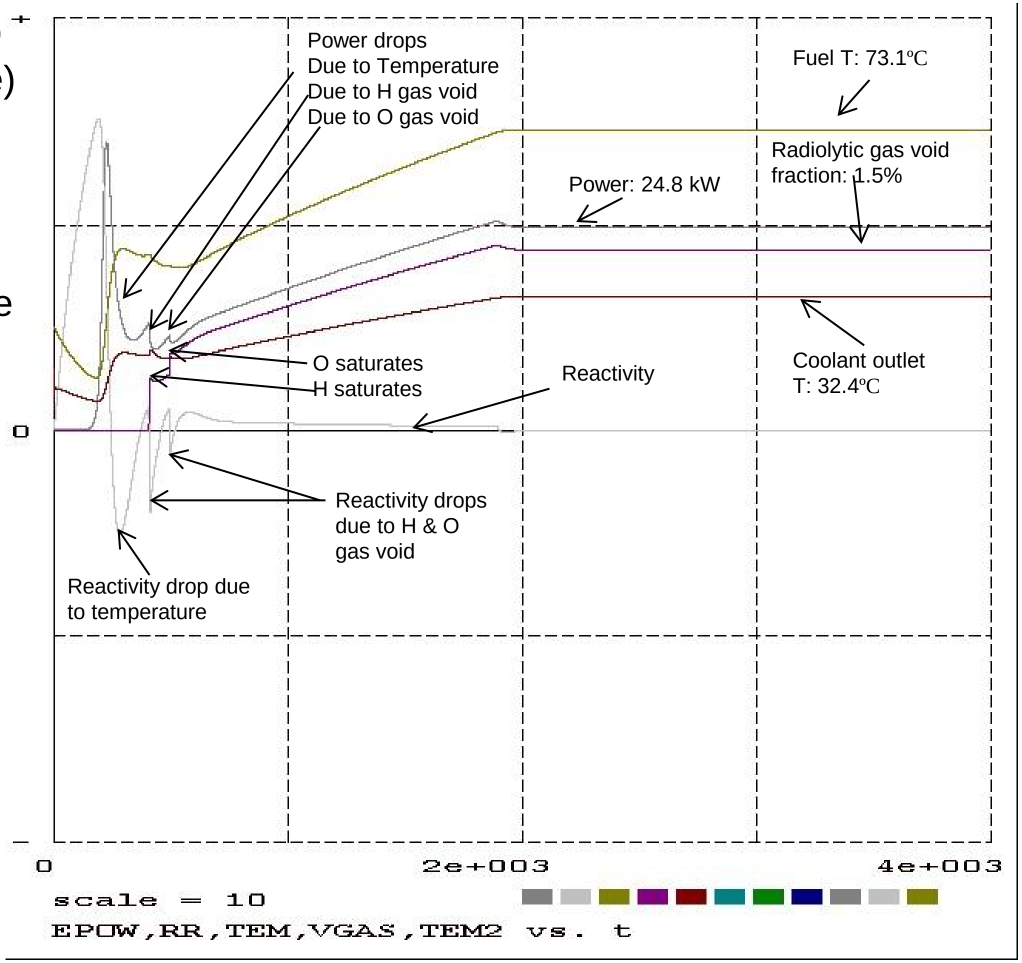
Effects combine: SUPO operating at 60ºC with 1.5% void had a total negative reactivity feedback due to temperature and void of (60-20)*(-$0.0344) + 0.015*(-$34.23) = -$1.89

Dynamics – Startup & Transition to Steady-State

System Model of SUPO with $1.90 excess reactivity (normalized scale)

Experimental Data

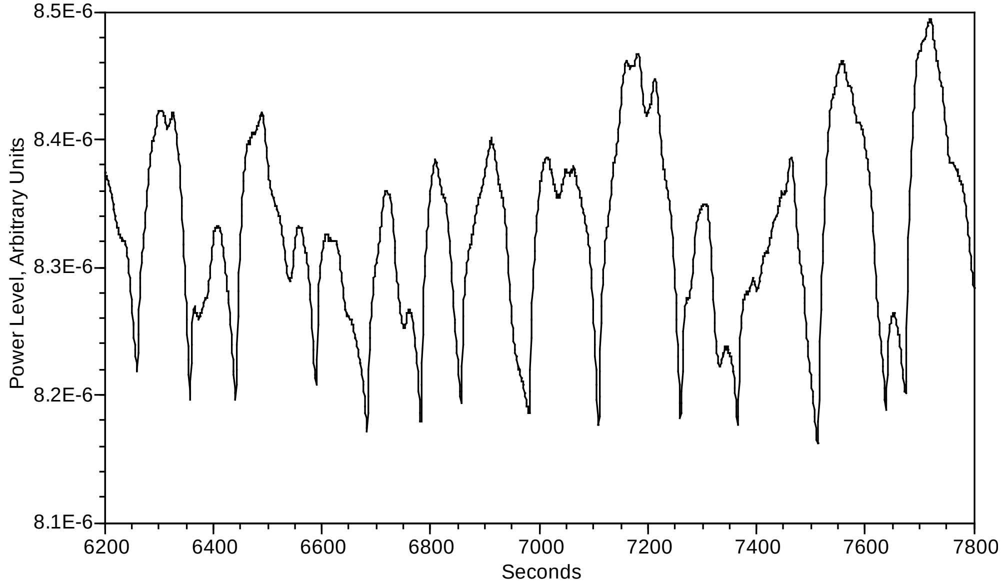
- 25 kW
- 75ºC fuel temperature
- 35ºC outlet coolant temperature



Dynamics – Power Oscillations at Steady-State

Typical oscillations due to radiolytic gas formation and transport

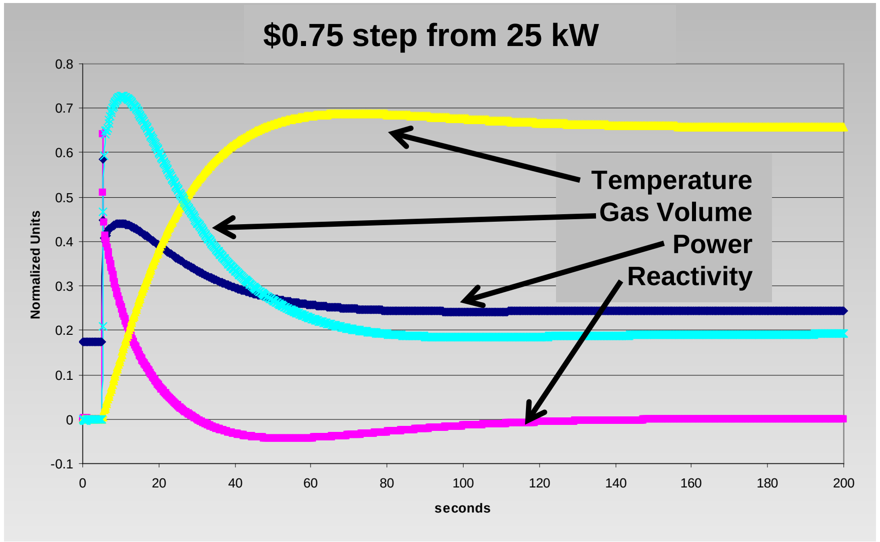
FIGURE 2
Oscillations at "Steady State" in Sheba 2
Data provided by Charlene Cappiello

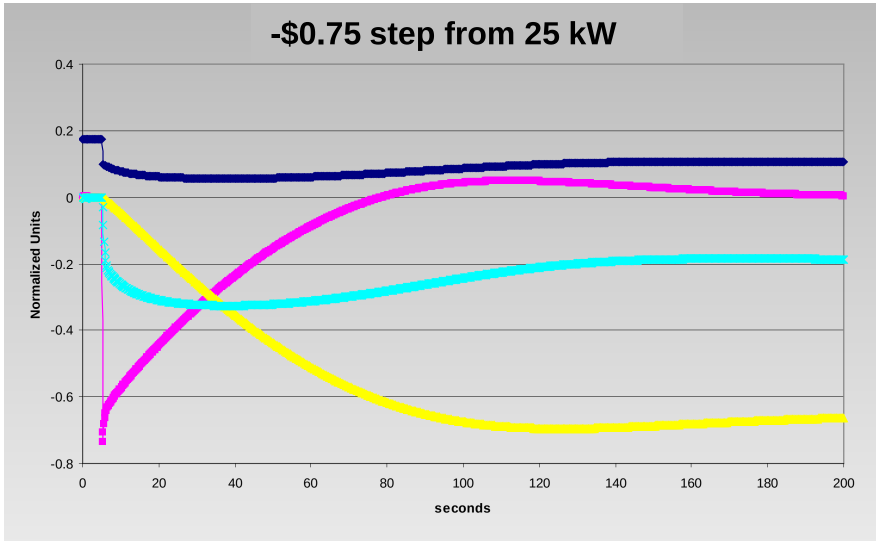


(Taken from SHEBA Run 11/9/95)

Dynamics – Stability

An aqueous homogeneous reactor (AHR) initially at steady-state re-establishes a new steady-state condition on its own following a reactivity perturbation





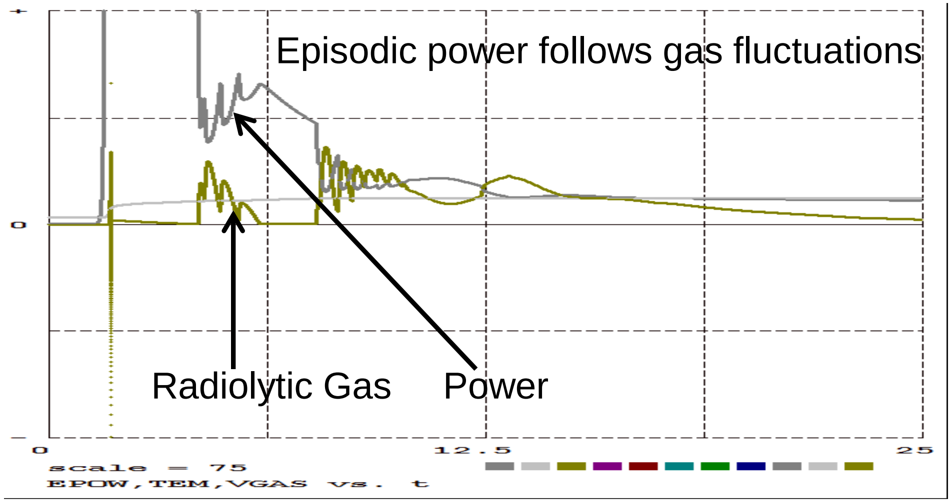
- No sustained reactivity oscillations
- Small oscillation about critical
- Quick reactivity feedback
- Reactor's physical response very mild

Dynamics – Response to Rate of Reactivity Insertion

Total inserted reactivity: $1.90 (KEWB A-2 Model)

Rate ($/sec)	kW max	Time of Peak (sec)
0.01	122	79
0.1	1,038	11.3
1.0	20,068	1.75
10.0	31,008	0.51

Power & Gas Dynamics Detail for $1.0/sec



Auxiliary System Effects – Gas Handling (SUPO Example)

Clogged Plenum

T (min)	P (atm)	kW	T (ºC)	Void (%)
0.0	0.80	24.90	64.18	2.09
10	2.38	26.95	67.52	1.66
20	5.14	28.26	69.61	1.39
30	9.28	29.17	71.06	1.21
40	14.79	29.83	72.10	1.07
50	21.69	30.33	72.88	0.97
60	29.97	30.73	73.50	0.89

Clogged plenum doubles pressure approximately every 10 minutes

Diminished Cover Gas Flow

Flow (%)	kW	T (ºC)	Void (%)
100	24.90	64.18	2.09
75	24.90	64.18	2.09
50	24.90	64.19	2.09
25	24.92	64.22	2.08
0	26.65	67.03	1.72

Loss of flow reduces pressure above solution allowing more rapid gas release

Pressure in plenum is governed by cover gas flow and exit of radiolytic gas escaping fuel surface

Auxiliary System Effects – Cooling Water (SUPO Example)

Coolant inlet Temperature

Inlet T (ºC)	kW	T (ºC)	Void (%)
5	24.90	64.18	2.09
10	23.01	65.16	1.96
15	21.15	66.15	1.83
20	19.31	67.17	1.70
25	17.50	68.20	1.57

System maintains thermal energy balance between heat of fissions and extraction by cooling system

% Coolant Flow

Flow (%)	kW	T (ºC)	Void (%)
200	28.47	62.41	2.32
175	27.91	62.68	2.29
150	27.20	63.03	2.24
125	26.24	63.50	2.18
100	24.90	64.18	2.09
75	22.88	65.23	1.95
50	19.55	67.04	1.72
25	13.18	70.78	1.23
0	0.28	88.04	0.03

Summary – Characteristics of Fissile Solution Systems

- Ability of fuel to flow rapidly during operation due to thermal forces and radiolytic gas dynamics drives the physics of these systems
- Exhibit high negative reactivity feedback due to fuel temperature increase and radiolytic gas generated void (both decrease fuel density)
- Are well-damped systems and bounded reactivity excursions result in bounded (new) steady-state operating condition
- Very docile and slow to respond due to long neutron lifetime and high thermal inertia of the fuel (specific heat of fuel is an order of magnitude greater than solid fuels).
- Operation requires large excess reactivity to be available ($5.00 or more)
- Sensitive to auxiliary systems such as cooling water, gas handling, and water makeup; small changes can have large effects due to the large feedbacks